The cross section of the tau-neutrino

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The DONuT experiment collected data in 1997 and published first results in 2000 based on four observed ν_τ charged-current (CC) interactions. The final analysis of the data collected in the experiment is presented in this paper, based on 3.6×10^{17} protons on target using the 800 GeV Tevatron beam at Fermilab. The number of observed ν_τ CC interactions is 11, in addition to 553 observed ν_μ and ν_e CC interactions. From this data we estimate the relative and absolute average ν_τ CC cross sections to be $xx \times 10^{-zz}$ cm^{-2}, in agreement with expectations from the Standard Model.

PACS numbers: 14.60.Lm, 14.60.Pq, 96.40.Tv

August 21, 2006

I. INTRODUCTION

The tau neutrino, ν_τ, was assigned its place in the Standard Model after its weak partner, the tau lepton, τ, was discovered in 1973 [1]. The observation of identifiable ν_τ interactions, in a manner similar to ν_e and ν_μ interactions, did not immediately follow. The difficulty of measuring ν_τ interactions was due to the relative scarcity of the sources of ν_τ and having sufficiently powerful detection methods to unambiguously identify the τ lepton produced in the charged-current interactions. These challenges were overcome in the observation of four ν_τ interactions by our group, the DONuT (**D**irect **O**bservation of **Nu**-**T**au) collaboration, in 2000 [2], twenty-seven years after the τ was found. Since that report, we have finished the analysis of the data, more than doubling the total number of found neutrino interactions of all flavors. We report on the results of this analysis here, which completes the experiment.

The experiment, equipment and techniques, have been described in detail elsewhere [3][4]. Here we give a summary, reviewing the essential parts of the beamline, detectors and analysis methods.

The location of vertices in the emulsion data, tagging leptons and the subsequent search for secondary vertices, were accomplished with high efficiency. This allowed a detailed event-by-event analysis with small and well-known background levels. Further, the large amount of information in the emulsion/spectrometer system permitted the use of powerful multivariate methods yielding probabilities of each candidate event for signal and background.

This report is a summary of the final sample of ν_τ, ν_e, and ν_μ interactions in the emulsion, and from this sample, the measured ν_τ cross section is computed. An overview of the detector, with emphasis on the emulsion is given in Section 2 II. Section 3 refsec:xxx details the important features and limitations of the neutrino interaction analysis, the secondary vertex analysis, and tau-identification methods and efficiencies. Section 3 refsec:xxx is a survey of the entire interaction data set, and comparisons with what is expected. The τ-containing candidate events are described in Section 4 refsec:xxx together with the all the charm-containing events that were found. Section 5 refsec:xxx details the systematic uncertainties relevant to the cross section determination, which is summarized in Section 6 refsec:xxx .

II. NEUTRINO BEAM AND DETECTOR

The primary source of tau neutrinos in DONuT were leptonic decays of D_s mesons produced by 800 GeV protons from the TeVatron at Fermilab. The protons were dumped into a solid block of tungsten alloy, with a typical intensity of 8×10^{12} protons for 20 seconds each minute, or about 20 kW of power. The D_s mesons yield two neutrinos in this decay mode within a distance of a few millimeters, much less than the interaction length of six centimeters. Immediately following the beam dump were two dipole magnets with solid steel poles, providing both absorption of interaction products and deflection of high-energy muons away from the beam center. Following the magnets was an additional 18 m of passive steel shielding limited to within 2 m of the beamline. Emerging at the end of this shield were neutrinos and muons. The muons were mostly contained in horizontal fan-like distributions, on each side of the centerline. The neutrino beam design is shown in Fig. 1 reffig:xxx.

The target for the neutrinos was 250 kg of nuclear emulsion stacked in modular fashion along the beamline. The emulsion target was the heart of DONuT, its capabilities and performance were matched to task of recognizing neutrino interactions containing tau leptons. The signature of ν_τ charged-current (CC) interactions was the decay topology: 86% of τ decays are to a single charged particle (lepton or hadron) and the typical decay length in the emulsion is only 2 mm. The emulsion target provided micrometer precision in tracking the products of the neutrino interactions, resolving the τ decay vertex, which was usually only a kink in the visible track. A total of seven emulsion modules in the target station were exposed, with a maximum of four modules in place at any time during the experiment. The DONuT emulsion modules were the first modern implementation of a design that interleaves metallic sheets (stainless steel) with emulsion sheets to blend high mass for interactions with high precision for tau recognition. Two of the three module types incorporated steel, while one module employed a third type, which used only emulsion sheets without steel. The three designs are shown in Fig. 2 reffig:xxx.

The information in small volumes of the emulsion was fully digitized and incorporated into the analysis in a manner similar to an electronic detector, though without time information. Integrated into the emulsion target station were 44 planes of scintillating fiber detectors, used for reconstruction of the interaction vertex. This vertex information permitted the scanning and digitization of only a small volume of the emulsion target, appropriate to the capability of the automatic scanning machines. The emulsion target station was followed by spectrometer consisting of a large-aperture dipole magnet and drift chambers. A lead-glass calorimeter supplemented the emulsion as a way to identify electrons. Behind the calorimeter, muons were tagged with a steel and proportional tube system. Lepton identification was important in DONuT, since an interaction produced with a charmed meson could have a topology similar to the τ signal. A ν_τ interaction does not have a charged lepton from the primary vertex. The plan of the spectrometer is shown in Fig. 3 reffig:xxx with the emulsion target area featured in Figure 4 reffig:xxx .

III. DATA COLLECTION AND REDUCTION

A. Triggering and data acquisition

The electronic detectors required a prompt trigger for the digitizing and readout electronics. A simple and efficient trigger for recording neutrino interactions required that no charged particles entered the emulsion from upstream and at least one charged particle emerged from an emulsion target. This trigger was formed by a series of scintillation counters consisting of a veto wall upstream of the emulsion target stand and three hodoscope planes distributed between and downstream of the emulsion modules. The veto wall consisted of 10 counters and covered a total area of 140 cm $\times$ 152 cm. The dimensions of each counter were 30.5 cm in x, 152 cm in y, and 10 cm in z. For muons, the veto wall efficiency was determined to be better than 99.9%.

Two planes of scintillating fibers, T1 and T2, were located downstream of the second and fourth target modules, respectively. Each plane was 70 cm $\times$ 70 cm in area and segmented into eight (T1) or nine (T2) 10 cm bundles. A third scintillator hodoscope, T3, was located downstream of the target/SFT box. It was composed of eight counters, each 10 cm $\times$ 80 cm and 5 mm thick. Two triggers were used during the course of the experiment. The design goal of the trigger system was to keep data acquisition live time at greater than 85%, which would correspond to a trigger rate of 6 Hz: The main trigger (Trigger A) required: (1) hits in T1, T2 and T3 consistent with two or more charged tracks; (2) track angles > 250 mrad; and (3) no hits in the veto wall. The detector elements for Trigger A are shown in Fig. 4 reffig:xxx . Trigger A was the sole physics trigger for the first 53% of the recorded data. The fact that it required more than one charged particle compromised the efficiency for triggering on single multiplicity neutrino interactions. This compromise was necessary since the trigger rate for a single track was very high due to background processes initiated by throughgoing muons from the dump. Because of the limited speed of the SFT readout system, discussed above, the live-time of the experiment would have dropped far below the design goal. The measured average rate for trigger A was 4.5 Hz corresponding to a live-time of 90%. During the final 6 weeks of data taking (47% of the recorded data), a second trigger (Trigger B) was implemented in order to include single track interactions that were lost in Trigger A. This trigger used the MLUs to require a proper 1-track pattern and, in addition, required at least one minimum ionizing track in the electromagnetic calorimeter. With the addition of Trigger B, the trigger rate increased to 5.5 Hz and the live-time decreased to 87%.

The efficiency of the triggers for neutrino interactions was calculated using simulated events with actual geometries and measured efficiencies for each counter. It was estimated that the efficiency was 98% for triggering on charged-current interactions of electron- and muon-neutrinos, 84% for neutral-current interactions, and 97% for nt interactions.

The architecture of the data aquisition was based on the Fermilab DART product [7] citeref:dart, using VME-based microprocessors to control the transport of data from the VME buffers to a host computer. The host computer served as both the data monitor and as the data logger to tape (Exabyte 3500). The average event size was 100 kB; with a throughput of 10 MB per beam cycle of one minute.

B. Filtering, stripping and scanning

A total of 6.6×10^6 triggers for 3.6×10^{17} protons on target were recorded onto tape. However, from calculations, only about 10^3 neutrino interactions were expected for this proton exposure. This implied that the great majority of the triggers were background processes satisfying the simple trigger requirements of Section “3.3” III A. Data from the electronic detectors were used to extract the neutrino interaction candidates in a two-step process.

First, data from the SFT and from the drift chambers were used to reconstruct tracks and to search for a vertex near one of the emulsion targets. This filter reduced the number of events by a factor of 300.

In the second step, the filtered triggers were examined individually by a physicist using graphical display software. This stage rejected events originating from particle showers produced by high-energy muons and checked for errors in reconstruction and other pathologies. About 90% of the events were rejected quickly and with high confidence. This visual scanning reduced the data by another factor of 20, yielding 868 interaction candidates.

The estimated total efficiency for retaining a tau neutrino interaction vertex with the electronic detectors was 75%.

C. Neutrino event sample

The result of the filtering and scanning selection was the neutrino interaction data sample. This sample of 868 events were highly likely to be interactions from (all flavors) of neutrinos with the interaction vertex located within the fiducial volume of the emulsion. In this sample, we report on the complete analysis of 552 events with the neutrino interaction vertex located in the emulsion. In the remainder of this paper, we will refer to these 552 as the "located" events. Although locating the vertex in the emulsion was attempted for each of the 870 events, some of these events are difficult to find due to factors discussed below in Sec. "3.1" refsec:xxx. The ν_μ CC events, however, are identifiable using only the electronic spectrometer information. There are 400(??) events in the sample of 868, which have an identified muon track (40%??). This compares well to the 38%(??) rate found for the sample of 552 located in the emulsion. No further analysis was done for the events in the interaction sample that are not located.

IV. OVERVIEW OF DATA ANALYSIS

A. Event reconstruction

Event reconstruction is a three step process. First, the information from the electronic detectors is used to fit charged tracks and reconstruct the vertex from the neutrino interaction. Next, this vertex and its estimated errors are used to determine the location and size of the volume in the emulsion that is subsequently scanned. Finally, once the emulsion information is digitized, a second round of track fitting and vertex fitting was performed. The electronic detectors were needed to predict a vertex position with a precision of about 1 mm transverse and 10 mm along the neutrino beam direction. This volume size was well-matched to the capabilities of the emulsion scanning machines used at Nagoya University.

The scintillating fiber tracker, which was interleaved between the four emulsion module stations, was the principal detector for making the initial vertex prediction. A complete reconstruction of the neutrino vertex, with all tracks unambiguously fit spatially, was made for only about 30% of the final sample. These were usually low-multiplicity vertices located near the downstream end of an emulsion module. Each module corresponded to 2.5 to 3 radiation lengths and 0.2 interaction lengths so secondary interactions giving rise to more charged particles was a common occurrence. In the majority of the events, tracks could be easily constructed in a single view (two-dimensional tracks) but not in space without ambiguous solutions. Nevertheless, this information was usually sufficient for predicting volumes used in event location in the emulsion. Once the vertex was located using the emulsion information, all spatial ambiguity of the neutrino interaction tracks was resolved.

B. Reconstruction of emulsion information

1. *Event location*

Using the information from the SFT, the approximate location of the neutrino interaction vertices were reconstructed and used to locate these events within the volume of the emulsion target. The typical volume that was digitized for event location was 5 mm × 5 mm × 15 mm. Because the emulsion target was constructed by stacking emulsion plates that must be disassembled for development, a method for precisely realigning the plates was employed. A large number of background tracks recorded in the read-out volume (high energy muons from the beam dump) were used. It was these tracks that were used to precisely align the emulsion layers. The complete tracks were built layer by layer. Each track recognized in an emulsion layer (micro-track) was examined to see if it had a connectable micro-track in the adjacent emulsion layers. The parameters of interest are the distance between the emulsion layers (L), the relative shifts in transverse direction (x, y) and the shrinkage of the emulsion layers. The measured $\Delta\theta$ was also affected by emulsion distortions. From the angular and position displacement distributions the above parameters can be determined.

Once a predicted emulsion volume in the target was scanned and aligned, track pairs were examined to see if they formed a vertex. To select these tracks, the following criteria were applied: (1) Tracks must start within the volume and have no connectable micro-tracks in the two adjacent upstream emulsion layers to reject the penetrating muon tracks. (2) Tracks must be constructed from at least three micro-tracks and have a good χ^2 fit. These requirements reduce the number of low momentum tracks. (3) The remaining tracks were tested for vertex topology. At least three (two?) tracks were required to be associated where all impact parameters at the best vertex position were less than 4 μm. After these vertex requirements were imposed, only a few vertex candidates remained. To confirm a vertex candidate, *(i)* the emulsion plates near the vertex point were studied using a manually controlled microscope to check for consistency of the neutrino interaction hypothesis (i.e. neutral particle interaction), and *(ii)* the emulsion track information was compared with the hits in the SFT to verify all tracks were associated with the same event.

2. *Momentum from Coulomb scattering*

Although the thickness of the emulsion modules was a disadvantage in reconstructing the vertices from the spectrometer data, this depth was also used to the benefit of the experiment. The very high spatial precision of the tracking along with an adequate sampling rate was used to calculate the momentum of tracks extracted from the visible scattering between emulsion plates. In order to gain maximum sensitivity, the emulsion data was subjected to calibration procedure to remove local geometrical distortions in the emulsion layers using the always-present penetrating muon tracks. Details in this procedure are given in [3].

The upper limit of the momentum measured using scattering was limited by the number of samples, the angle of the track, the quality of the emulsion data and the type of emulsion module. The typical upper limit (1 σ) was 25 GeV/c. A comparison of track momenta measured with both the emulsion and spectrometer is shown in Fig reffig:xxx.

V. SECONDARY VERTEX ANALYSIS

For the located events, the emulsion was digitized again for a volume optimized around the position of the vertex. This volume was smaller, 2.5 mm $\times$ 2.5 mm $\times$ 12 mm. The track reconstruction algorithm was the same as that used for vertex location. The tau decay search was divided into three distinct categories distinguished by topology: (1) one-prong decays where the tau passed through at least one emulsion layer (Long decay search), (2) one-prong decays where the only the daughter was recorded in emulsion (Short decay search) and (3) three-prong or trident decays where the tau passed through at least one layer (trident search). Details of the Long and Short decay search have been previously published [3].

The *Long decay search* imposed the following criteria:

1. The parent track length was $<$ 10 mm.
2. The impact parameter of the parent to the primary vertex (i) was $<$ 5 μm if there are at least two segments, or (ii) was $<$ (5 + 0.01$\times\delta z$) μm if there was one segment, where δz is the distance from parent segment to vertex.
3. The minimum distance between extrapolated parent and daughter tracks (i) was $<$ 5 μm if there are at least two segments, or (ii) was $<$ 5 + 0.01$\times\delta z$) μm if there was only one parent segment.
4. The kink angle was $>$ 4 times the angular measurement error OR the impact parameter of the daughter to the primary vertex was $>$ 4 times the error in the position.

5. The digitized parent and daughter tracks may or may not coalesce: (*i*) If the parent and daughter tracks are distinct the parent must be at least one segment and the daughter at least three segments. (*ii*) If the parent and daughter tracks are not distinct in the digitized data then part assigned to the parent track must be at least four segments and the daughter part at least four segments.

Candidate tracks passing the above criteria were checked by a physicist using a microscope to ensure that the kink track could not be associated with emulsion tracks upstream of the vertex and was not due to alignment problems, e^+e^- pairs or other pathologies.

The *Short decay search* required the following criteria:

1. The daughter track was at least three segments,

2. The impact parameter to the primary vertex was $< 200\ \mu$m.

Again, the candidate daughter track was checked visually to insure that it could not be connected upstream of the vertex. The above criteria are topological and were intended to find real kinks [[[and tridents]]]? in the data. This was the first step to extract tracks of interest, which were either actual decays or hadronic interactions in the modules. The criteria for separating decays, using criteria derived from kinematic considerations, is given in Section "4.5" V B, below.

A. Lepton tagging

If an electron or muon was associated with the primary vertex of the neutrino interaction then the interaction was rejected from the tau analysis, even if a secondary vertex were found. Lepton identification was achieved with the electronic spectrometer for both electrons and muons and the emulsion information was employed for electron identification. The muons were found by using proportional tube planes interleaved with steel for absorbing hadrons. A muon tag was assigned to a track if there were at least four of the possible six prop tube hits. The per tube efficiency for muons was measured to be 0.96, and the geometrical efficiency of the muon ID system was estimated by Monte Carlo to be 0.76, yielding an overall efficiency of 0.73.

The electron analysis was less straightforward since it involved several systems. Since the emulsion modules are 2 to 3 radiation lengths, most events containing electrons will exhibit showers in the scintillating fiber tracker and calorimeter. These two systems are used to find the most likely initial energy of the electron from an algorithm using both energy (pulse height) and geometrical shower development. Emulsion information can be used by searching for electron-positron track pairs within 20 μm of the track under investigation. This method was effective for vertices located in the upstream part of each module. The efficiency for electron tagging using the spectrometer was estimated using Monte Carlo to be 0.80. The electron tagging efficiency using emulsion data varied with depth from 0.86 for tracks passing through at least 2 X_0 to 0.0 for tracks at the last (downstream plate) with an integrated efficiency of 0.66.

B. Tau and charm recognition

1. *Topology and kinematics*

There were three analyses used to extract the tau signal. First, a relatively simple set of selection criteria was applied to the entire data set of 550 [??] events. This type of analysis was reported by us in a previous publication [2]. The second method used five parameters measured from the data (four parameters for 3-body decays) and compared the values to the expected 5-dimensional (or 4-dim) distributions from a Monte Carlo. A probability for each hypothesis (i.e tau, charm or background) was obtained from this multivariate analysis. A third analysis using artificial neural networks, trained on Monte Carlo, was used to extract tau events as well as classify the type of interaction (i.e. ν_e,

ν_μ, ν_τ, or neutral current).

The charged-current interactions of ν_τ produce a τ lepton that typically decays within 2 mm of its origin. Thus, the topological signature for tau events is a track from the primary vertex that gives a secondary vertex at a short distance consistent with the kinematics of the decay. As noted above, there must be no other lepton from the primary vertex. The second background of significance was hadronic interactions that appear in the emulsion data as a kinked track or a three-body decay. The following set of criteria was derived from Monte Carlo studies to efficiently extract the tau signal from with minimal background. It is a modified version of the selection criteria of [2]. For Long decays the cuts were:

- The parent angle w.r.t. the neutrino direction < 0.2 radians.
- The daughter angle w.r.t. the neutrino direction < 0.3 radians.
- The kink angle (for one-prong candidates) < 0.25 radians.
- The impact parameter to the primary vertex < 500 μm.
- The transverse momentum of the decay > 250 MeV/c for hadrons and electrons and > 100 MeV/c for muons.
- The daughter momentum > 1 GeV/c.
- The sum of the impact parameters of the daughters in three-body decays < 600 μm.

In the case of trident secondary vertices, at least one of the secondary tracks must pass all of the above requirements.

For Short decays the cuts were the same as above except that the kink angle cannot be defined since the parent angle is unknown. Here we replaced the kink angle by the minimum kink angle, which was defined as the angle between the daughter and a line passing through the primary vertex and the daughter track projected to the emulsion boundary.

The above criteria ...

2. *Mutivariate analysis*

The criteria above used for extracting a tau signal from background events had the advantages of being simple to apply and it produces results that are readily understood in terms of one-dimensional distributions. However, this simple analysis could not give accurate estimates for the probabilities of signal and background for individual events. A multivariate procedure was employed to determine the likelyhood of a particular event was taken from a set derived from the following hypotheses:

- Charged-current ν_τ interaction with one or three prong tau decay
- Charged-current ν_e or ν_μ interaction with charm one or three prong decay
- Neutrino interaction with one or three prong secondary interaction and no lepton found

The second and third hypotheses were the dominate backgrounds to the tau events, and were the only background processes considered in this analysis. Only events selected by secondary vertex analysis, detailed above, were submitted to the multivariate analysis.

A set of parameters, measured for each event, were the sole inputs to the analysis for all three event hypotheses. They were chosen to be easily and unambiguously measured in the emulsion data (supplemented by spectrometer information) and discriminate between the hypotheses. For n parameters, a n-dimensional probability density distribution for each hypothesis was computed using Monte Carlo generated events. Then the relative probability of event k sampled from the distribution of hypothesis i can be written as

$$P(\{x_k\}|i) = \frac{\Gamma_i \Pi(\{x\}|i)}{\Gamma_i \Pi(\{x\}|i) + \Sigma_{bkg}\Gamma_{bkg}\Pi(\{x\}|bkg)} \tag{1}$$

where $\{x\}$ is a set of the event's parameters, $\Pi(\{x\}|i)$ is the probability density function evaluated at a set of measured parameters, and Γ_i

is the prior probability of the event being an i type event. Note that Γ_i is independent of $\{x\}$ and gives the probability of a neutrino interaction that could give a result described by $\{x\}$. For the tau hypothesis, for example, Γ_i is computed from the ν_τ production processes and its interaction cross section in the emulsion target. The sum over the background only includes the two hypotheses other than i.

The parameter set for single-prong events found in the Long decay search consisted of the following five quantities:

1. The decay length of the parent track, L_{dec}
2. The kink angle, α
3. The daughter momentum, p_d
4. The parent track angle w.r.t. the neutrino, θ
5. The polar angle difference between lepton and recoil tracks, $\Delta\phi$

The parameters are self-explainatory, except $\Delta\phi$, which needs clarification. Let the z axis be the direction of the neutrino. Then form the sum of the unit vectors along the direction of each track projected onto the x-y plane excluding the parent track of the decay (assumed to be the lepton). Then the difference in angle in this plane between the parent and the sum of the recoil tracks is $\Delta\phi$. See Figure XX. Since the lepton and recoil momentum are equal and opposite directions, $\Delta\phi$ is peaked around π radians for true tau events. It provides discrimination of interaction and charm backgrounds.

For 3-prong decay candidates from the Long decay search, the daughter momentum and kink angle are replaced by the sum the impact parameters of the daughters at the interaction vertex, ΣIP. This sum, divided by three, is a measure of the value of $c\tau$ for each decay. It provides discrimination between the three hypotheses, since the tau leptons have short lifetimes (89μm) compared with charm (160μm average for all charm) and interactions (independent of decay length). The daughter momenta were not used in the analysis.

The multivariate analysis can also be used for the events from the Short decay search. Here, however, the true decay point was not seen so that the kink angle, the parent angle were not known. Also, the $\Delta\phi$ parameter was compromised without knowledge of the parent angle. [need more here]

figure -The kink event parameters

figure - The Delta Phi parameter

figure- The trident event parameters

The daughter momentum, p_d, was measured either using the deflection of the track in the spectrometer magnet or using the emulsion data to measure the momentum from multiple scattering. This parameter was only used for the kink events. The uncertainty in the multiple scattering measurement of momentum was due to the number of track segments in the emulsion. The lower momentum tracks often did not reach the drift chambers, and, therefore, had no spectrometer momentum measurement. Thus the momentum measurements were often complimentary, with the tracks with large momenta (often muons) were better measured with the spectrometer, and the low momentum tracks were reliably measured in the emulsion data.

Table reftbl:xxx summarizes the prior probabilities for all tau and charged charm candidates for both kink and trident events. The candidate column refers to the type of candidate, and the material column refers to where the decay occurs.

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Table reftbl:xxx lists the results, which are relative probabilities of each hypothesis for each of the tau and charged charm candidates.

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3. *Analysis using Neural Networks*

The technique of Artificial Neural Networks (ANN) was used in the DONUT data analysis for the cases where event classification was needed. The technique is illustrated in Fig. "A1" reffig:xxx. The network consists of several layers of neurons: the input layer, the output layer and several hidden layers. The weights w_{ij} represent the strength of the connection ij. The input to the network is the vector $\mathbf{x} = (x_1, x_2, ..., x_n)$, with components the variables $\{x_i, i = 1, n\}$ and the output is the vector $\mathbf{y} = (y_1, y_2, ..., y_n)$. The training of the network is performed by presenting the ANN with pairs of vectors ($\mathbf{x}$, $\mathbf{y}$) and adjusting the weights w_{ij} in such a way as to minimize a cost function. The training set can be either experimental information or Monte Carlo. In the latter case special attention must be taken to make sure that the Monte Carlo describes the data satisfactorily.

In DONUT ANNs were used in the following analyses: *(i)* Selection of spectrometer events to scanned and subsequently reconstructed. For this previously selected by eye events were used as the training set. Using this technique a second selection became possible without visual scan. *(ii)* Classification of neutrino interactions into CC and NC and subsequently into muon neutrino and electron neutrino interactions. In this case the training set was consisting of Monte Carlo events and special effort was made to make sure that Monte Carlo described well the data. *(iii)* Selection of tau neutrino interactions and separation from interactions imitating taus, namely, charm production by muon and or electron neutrinos and background from hadron scattering. In this case each event was characterized by its probability to belong to each of the three categories (tau, charm, hadron scattering) was determined. The training set was provided from Monte Carlo.

Details of how ANN analysis was implemented will be given in sections ****.

VI. SURVEY OF DATA

A. Expected composition

The expected number of interactions, along with the type of interaction was predicted by using known and measured quantities in a Monte Carlo. One must define interaction "type" by the way an event was classified in DONuT. Charged-current interactions of ν_μ, ν_e and ν_τ were defined by recognition of the lepton at the primary vertex. However, the NC type of event was defined as all events not recognized as CC events. This class of event included not only genuine NC events, but also those CC events where the lepton was not identified. Also, interactions could be distinguished only for CC interactions where the sign of the muon was determined in the magnetic spectrometer. Table I shows the expected fraction and number of events of each of the four interaction types measured in the experiment. Note that although the prompt (from charm decays) and non-prompt (from π and K decays) components are separated in the calculation, they are not directly distinguished in the analysis.

B. ν_μ CC events

The identification of muons using the spectrometer was straightforward and was efficient, so this category of interactions was considered the most reliable. The muons were selected by requiring at least four hits recorded in the proportional tube muon system out of a possible maximum of six. The efficiency of this tag for ν_μ CC events was estimated from Monte Carlo to be 0.75 $\pm$ 0.03. The number of ν_μ CC events found in the data was 210 events, which gives the fraction of the total located events as 0.38 $\pm$ 0.03. The expected fraction of the muon sample was highly affected by the number of muon neutrinos that originated from decays of $\pi^\pm$(and K$^\pm$ in the primary beam dump. Although there is only a small (10^{-3}) probability that they decay with $p > 1$ GeV/c, the number of estimated ν_μs from π and K decays (which we call "non-prompt") is comparable to the ν_μs from decays of charm mesons (termed "prompt" sources). The value of this non-prompt fraction of ν_μ events can be estimated by direct, Monte Carlo calculation, or by extraction from the data. In the data, very few ν_e interactions are likely to be from non-prompt sources. The number of ν_e CC events should be very nearly the same as that from the prompt part of the ν_μ flux. Also, momentum spectrum of muons from ν_μ CC interactions will have two different components. The different methods yield consistent values for the ratio of prompt muon neutrinos to the sum of prompt and non-prompt ν_μ. A FLUKA-based Monte Carlo result was used for the determining the non-prompt fraction as it produced spectra and yields most consistent with the observations. The ratio of prompt to total ν_μ CC interactions was estimated to be 0.57 ± 0.07.

The ratio of the number of neutrino interactions with μ^+ to the number with μ^- should be computable from the cross sections of neutrinos and anti-neutrinos as well as the detector efficiencies and acceptances. The naive estimate of 0.5 for this ratio was modified by Monte Carlo computations to 0.63. This ratio from the 553 located events was 0.67 ± 0.08.

There are three events in the located sample that have two identified muons. One event has muons of opposite sign with one from the primary interaction vertex and the other from a secondary, decay vertex. This is event is identified as a ν_μ CC interaction producing a charmed meson. The other two dimuon events are same-sign tracks, which probably indicates that one of the tracks, a charged π, decays in-flight. The momentum spectra for the muons from the located ν_μ CC events are presented in Figure 5 reffig:xxx.

C. ν_e CC events

1. Electron identification methods

The ν_e interactions comprised the second largest set of events, after the ν_μ events. Both the ν_e and the ν_μ events had the decays of charm particles in the dump as their primary source. However, only 5%(??) of the located ν_e events originated from non-prompt sources. The identification of electrons, essential to classifying ν_e CC events, was not as straightforward as muon identification. In DONuT, the primary method was to use the scintillating fiber system to record shower development in conjunction with energy in the lead glass calorimeter. Since each emulsion module was 2 to 3 radiation lengths in thickness, the total material in the path of an electron could be as large as 9 radiation lengths. Thus, the target mass, interleaved with fine-grained detectors, serves as a calorimeter in itself. The lead glass, 7 m away, served to record the electromagnetic energy escaping from the target/fiber system and was primary used to supplement the data for interactions in the third and fourth (last) emulsion target modules. For electrons that traversed at least two radiation lengths in the emulsion modules, the emulsion data was used to search for e^+e^- tracks (from bremstrahlung photons) within 50 μm along the length of each track attached to the primary vertex. Monte Carlo studies were used to estimate the electron tagging efficiency for the neutrino energy spectrum expected from charm decays. It was found to be 0.80. It was not very sensitive to possible systematic shifts in the spectrum from variation in the production models since the method is most effective for high-energy electrons ($E > 20$ GeV, efficiency 0.88). The mean expected electron energy form CC interactions is 35 GeV(??).

2. Electron energy estimates and ν_e CC spectrum

The target/fiber system, used for electron ID, was also used to estimate the electron (or gamma) energy. Since the scintillating fiber system response was calibrated to minimum ionizing particles, the total pulse height in a shower could be summed for each station providing a direct measure of energy. The energy estimates at each station were input variables for an algorithm to compute electron energy from shower development. The calorimeter information was added for showers that penetrated less than six radiation lengths of emulsion (approximate shower maximum). This energy resolution, $\Delta E/E$, from Monte Carlo events was 30%.

Since the beamline could not be configured for transport of electrons, electron ID relied heavily on Monte Carlo simulation. A selection of probable electrons from interactions in the last module, analyzed for momentum in the spectrometer and energy in the calorimeter, showed that the calorimeter calibration was consistent with the muon calibration method.

VII. NU-TAU SIGNAL

The methods described in Sections "4.3" refsec:xxx, "4.4" refsec:xxx, and "4.5" refsec:xxx applied to the 553 located events yielded the results for the neutrino interactions with an identified τ lepton. The list of events with a tau candidate is listed in Table "XX" II .

VIII. SYSTEMATIC UNCERTAINTIES

A. Protons on target

The number of 800 GeV protons that struck the dump were measured by devices that integrate charge collected from secondary emission from a foil. These monitors were calibrated with a beta source before the experiment began. Several times during the course of the run, these devices were calibrated against coil pickups and other monitors installed in the accelerator extraction complex. These checks showed that these primary beam monitors were consistent within 5% at intensities of 5×10^{12} to 1×10^{13} protons per spill. Losses in the beamline were negligible ($\approx 10^{-5}$) and no other corrections were applied.

The monitors were digitized and recorded at the experiment, and gated by the triggering electronics. The total of 3.54×10^{17} protons were recorded during the live-time of the experiment. A systematic uncertainty of 5% was assigned to the value of the total protons on the dump.

B. Neutrino production from 800 GeV protons

The tau-neutrino cross section on nucleons can be measured relative to a known process, such as the muon-neutrino interaction cross section (relative measurement), or directly, given the flux of tau-neutrinos produced in the dump (absolute measurement). The cross sections from both methods are calculated in Section 8 refsec:xxx, and rely on knowing the flux at the emulsion targets as a function of energy. The estimate of the neutrino flux, absolute or relative to each other, required an estimate of the production of all significant sources of neutrinos from proton interactions in the dump. These sources of ν_τ, as well as ν_μ and ν_e, are primarily charmed mesons. Their cross sections and branching ratios, extracted from the literature, were incorporated into the analysis. For the absolute measurement, the $\nu_t au$ flux is estimated from the following terms:

1. the production of D_s, $D^\pm$, Λ_c and $B^\pm$ hadrons from 800 GeV proton interactions
2. the decay form factor for each process
3. the decay branching fractions of $\tau \to \nu_\tau X$
4. the acceptance of produced tau-neutrinos passing through an emulsion module

Terms (1), (2) and (3) are either direct measurements taken from the published literature, or are estimates from other measurements extrapolated to the relevant energy of this experiment. The statistical and systematic uncertainties are substantial. Terms (1) and (2) constituted the major source of uncertainty in the absolute cross section. Table III gives a summary the measurements used in this calculation.
In Table III, the values for α, n and b were used in the simulated production of all charm states that give rise to neutrinos.

The effect of varying the values listed in Table III on the number of neutrino interactions in the emulsion was estimated by changing each value by one standard deviation in the Monte Carlo. (Also listed in Table III.)

C. Electronic efficiencies

D. Analysis efficiencies

1. Filters and scanning

The process of selecting triggers as neutrino interaction candidates was a sequence of two operations: (1) an encoded filter applied to all triggered events, and (2) a scan of the remaining events by physicists using graphical displays. In (1) triggers were selected for an emulsion search by requiring that a vertex reconstructed from tracks be within an emulsion target. In addition, the event trigger timing between two counters was required to be within 10 ns, and showering from nearby muon interactions was required to be absent. The filter (1) reduced the triggers by a factor of 300 and from Monte Carlo studies was found to have efficiencies for keeping interactions to be 0.98 (for CC events) and 0.96 (for NC events).

The second reduction (2) was needed to eliminate common pathologies allowed by the filter (1). It reduced the data by a factor of 20, which kept the amount of emulsion data for scanning to a manageable level. The efficiency of (2) was found to be 0.865 ± 0.066 and the error is from systematic effects.

E. Location

The efficiency for locating the primary vertex in the emulsion was given directly as the ratio of the number events found and the number of events tried. This ratio is 553/868 or 0.637 ± 0.035.

F. Decay Search

The efficiency of the tau decay search was determined in two ways: (1) Monte Carlo estimates only, and (2) using secondary (hadronic) interactions found in the emulsion data during the decay search. The topological efficiencies, from restriction in decay length, and angles was derived directly from simulations of neutrino interactions. Other factors included emulsion data efficiency (both physical and software), and algorithm efficiency (Short and Long decay searches) using emulsion data.

The results obtained for method (1) are presented in Table IV. The estimate for the overall systematic uncertainties in these efficiencies is 5% (??).

Method (2) ignored the differences in the topology of the interaction sample and the decay sample and the decay efficiency is simply the ratio of the number of interactions found to the number expected.

IX. NU-TAU CROSS SECTION

X. CONCLUSIONS

Acknowledgments

We would like to thank the support staffs at Fermilab and the collaborating institutions. We acknowldge the support of the U.S. Department of Energy, the Japan Society for the Promotion of Science, the Japan-US Cooperative Research Program for High Energy Physics, the Ministry of Education, Science and Culture of Japan, the General Secretariat of Research and Technology of Greece, the Korean Research Foundation, and the DOE/OJI Program.

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citeref:dart
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citeNEUGEN
citeLEPTO
citeGEISHA
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TABLE I: Expected composition of the beam-dump neutrino beam.

	ν_e CC	ν_μ CC prompt	ν_μ CC non-prompt	ν_τ CC	NC
Fraction	0.238	0.199	0.159	0.018	0.382
Fraction $\times$ 553	132	110	88	10	212
Data	143	210		9	191
Difference	11	12		-1	-21

TABLE II: List of ν_τ events.

	Event (mm)	l_{decay} (rad)	α_{decay} (μm)	IP p_{dtr} (GeV/c)	p_τ (GeV/c)	$P(\tau)$	$P(c)$	$P(int)$
3024/30175	4.47	0.093	416	5.2	0.48	0.64	0.36	0.00
3039/01910	0.28	0.089	24	4.6	0.41	0.96	0.04	0.00
3140/22143	4.83	0.012	60	22.2	0.26	0.97	0.03	0.00
3333/17665	0.66	0.011	8	3	0.69	0.99	0.01	0.00
3024/18706	1.70	0.014	23	50	0.70	1.00	0.00	0.00
3139/22722	0.53*	0.022*	12	15.8	0.35			
3296/18816	0.80	0.054	38	5.0	0.27	0.71	0.29	0.00
		0.190	148	1.3	0.25			
		0.130	112	1.9	0.2			
3334/19920	8.88	0.017	147	11.6	0.20	1.00	0.00	0.00
		0.011	98	15.7	0.17			
		0.11	94	3.2	0.04			
3250/01713	0.83	0.133	110	1.3	00.17	0.71	0.03	0.26
		0.192	161	2/4 7 00.46				
		0.442	354	0.5	0.21			

TABLE III: Quantities used in the analysis to compute neutrino cross sections. The charm cross section in a material of atomic number, A, is assumed to be proportional to A^α. The charm production differential cross section is assumed to be proportional to $(1-|x_F|)^n exp(-bp_T^2)$.

Quantity	Value
$\sigma(\mathrm{pN} \rightarrow \mathrm{D}^{\pm}\mathrm{X})$	11.3 ± 2.2 mb
$\sigma(\mathrm{pN} \rightarrow \mathrm{D}^{0}\mathrm{X})$	27.4 ± 2.6 mb
$\sigma(\mathrm{pN} \rightarrow \mathrm{D}_s\mathrm{X})$	5.2 ± 0.7 mb
$\sigma(\mathrm{pN} \rightarrow \Lambda_c\mathrm{X})$	5.4 ± 2.1 mb
$\sigma_{tot}(\mathrm{pW})$	1650 mb
α	0.99 ± 0.03
n	7.7 ± 1.4
b	0.83 ± 0.22 (GeV/c)$^{-2}$

TABLE IV: ν_τ efficiencies.

	ν_τ CC	$\overline{\nu}_\tau$ CC
1-prong (hadronic decay)	0.52	0.54
1-prong (electronic decay)	0.62	0.68
1-prong (muonic decay)	0.63	0.69
3-prong decay	0.74	0.80
All	0.59	0.63